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| **Citation** | Lu, Bin, and Tomás Palacios. "High Breakdown ( > 1500 V ) AlGaN/ GaN HEMTs by Substrate-Transfer Technology." IEEE Electron Device Letters 31.9 (2010): 951–953. © Copyright 2010 IEEE |
| **As Published** | http://dx.doi.org/10.1109/led.2010.2052587 |
| **Publisher** | Institute of Electrical and Electronics Engineers (IEEE) |
| **Version** | Final published version |
| **Citable link** | http://hdl.handle.net/1721.1/72116 |
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# High Breakdown (> 1500 V) AlGaN/GaN HEMTs by Substrate-Transfer Technology

Bin Lu, *Student Member, IEEE*, and Tomás Palacios

***Abstract*—In this letter, we present a new technology to increase the breakdown voltage of AlGaN/GaN high-electron-mobility transistors (HEMTs) grown on Si substrates. This new technology is based on the removal of the original Si substrate and subsequent transfer of the AlGaN/GaN HEMT structure to an insulating carrier wafer (e.g., glass or polycrystalline AlN). By applying this new technology to standard AlGaN/GaN HEMTs grown on Si substrate, an AlGaN/GaN HEMT with breakdown voltage above 1500 V and specific on resistance of 5.3 $m\Omega \cdot cm^2$ has been achieved.**

***Index Terms*—AlGaN/GaN, breakdown, high-electron-mobility transistor (HEMT), power electronics, substrate transfer, wafer bonding.**

## I. Introduction

AlGaN/GaN high-electron-mobility transistors (HEMTs) have attracted a great interest for the next generation of power electronics. Due to their high-electron mobility $(\mu_e)$ and high critical electric field $(E_c)$, GaN-based power converters enable more efficient and compact power-conversion systems than the Si-based converters [1].

To reduce the cost of GaN-based power electronics, silicon is the most attractive substrate for the growth of AlGaN/GaN HEMT structures. Recently, crack-free AlGaN/GaN HEMT structures grown on 150-mm Si substrates have been reported in [2] with a sheet resistance of 260 $\Omega/\square$ and mobility of 1650 $cm^2/V \cdot s$.

In spite of the great potential of GaN-on-Si electronics, it is suggested in [3] and [4] that the maximum breakdown voltages of the AlGaN/GaN-on-Si HEMTs are limited by the Si substrate. For example, the breakdown voltages of AlGaN/GaN HEMTs with a total of 2-$\mu$m epitaxial layer on Si substrates are typically less than 800 V [4]–[6]. Several methods have been reported to improve the device breakdown voltage beyond 800 V, including increasing the epitaxial-layer thickness [5]–[7], doping the buffer with Fe or C [8], [9], using AlGaN-based buffer layers [3], and the use of Schottky-drain contacts [4]. Another alternative method is to use sapphire substrates. However, this substrate suffers from high cost, limited wafer size (up to 6 in) and poor thermal conductivity.

In this letter, we demonstrate a new technology based on the removal of the Si substrate to achieve high breakdown AlGaN/GaN HEMTs with only a 2-$\mu$m total epitaxial thickness. This technology can be applied to any wafer size, and it does not require a thick epitaxial layer, which reduces the cost and the wafer bow. By removing the Si (111) substrate and transferring the AlGaN/GaN HEMTs to a glass wafer, a breakdown voltage of more than 1500 V has been demonstrated.

## II. Device Fabrication

The devices were fabricated on an AlGaN/GaN heterostructure grown on a 4-in Si (111) substrate by Nitronex Corporation. The device structure has a 2-nm GaN cap, a 20-nm $Al_{0.26}Ga_{0.74}N$ barrier, and a 2-$\mu$m-thick GaN/AlGaN buffer. Additional details about the wafer growth can be found in [10]. Ti/Al/Ni/Au alloyed source and drain ohmic contacts were formed by rapid thermal annealing at 870 °C. Then, mesa isolation was achieved by $BCl_3/Cl_2$ plasma etching. Two-$\mu$m-long Ni/Au/Ni gates were deposited with a gate width $(W)$ of 100 $\mu$m. The transistors have a gate-to-source spacing $(L_{gs})$ of 1.5 $\mu$m and a gate-to-drain spacing $(L_{gd})$ varying from 5 to 20 $\mu$m. After finishing the standard AlGaN/GaN HEMTs fabrication, the top surface of the sample (Ga face) was bonded to a Si carrier wafer by adhesive bonding using benzocyclobutene (BCB) cured at 250 °C for 1 h [11]. Then, the Si (111) substrate was removed by $SF_6$ plasma etching, exposing the N-face of the 2-$\mu$m-thick GaN/AlGaN buffer. The N-face of the GaN/AlGaN buffer was then bonded to a glass wafer using BCB. Finally, the Si carrier wafer was released by $SF_6$ and $SF_6/O_2$ plasma etching, as shown in the process flow in Fig. 1. Although the samples used in this letter had an area of $2 \times 2$ $cm^2$, we have recently demonstrated the substrate removal and bonding of full 4-inch wafers [12]. The breakdown measurement setup consists of a Tektronix curve tracer connected to Agilent 34401A multimeter. Fluorinert was used to prevent surface flashover, and the substrate was left floating during the breakdown measurement.

## III. Experimental Results

The dc characteristics of the AlGaN/GaN HEMTs before and after the substrate transfer are shown in Fig. 2. The maximum drain current of the device transferred to the glass wafer drops by 28% with respect to the one before the substrate transfer, which is mainly due to the self-heating effect. Using the transmission-line method (TLM), the extracted sheet resistance of the unpassivated devices is reduced from 850 to 680 $\Omega/\square$ after the substrate transfer. Similar sheet-resistance reduction

Manuscript received March 30, 2010; accepted June 2, 2010. Date of publication July 23, 2010; date of current version August 25, 2010. This work was supported in part by M/A-COM and in part by the Department of Energy through the GIGA Project. The review of this letter was arranged by Editor G. Meneghesso.

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Digital Object Identifier 10.1109/LED.2010.2052587

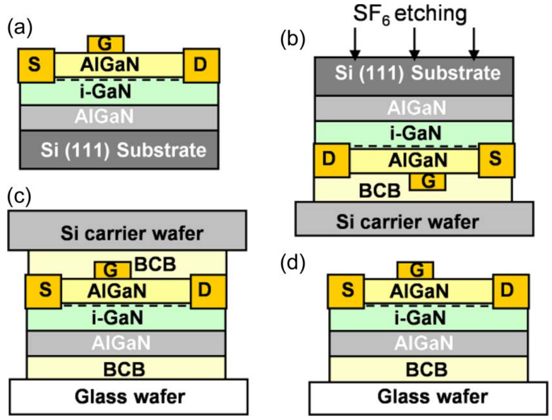


Fig. 1. Process flow of the substrate-transfer technology. (a) Standard AlGaN/GaN HEMT on Si substrate. (b) Bonding to a Si carrier wafer and Si (111) substrate removal. (c) GaN/AlGaN buffer bonded to a glass wafer. (d) Final device, after releasing the carrier wafer.

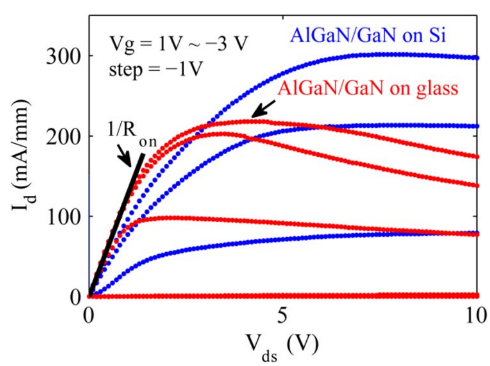


Fig. 2. $I_d$–$V_{\rm ds}$ characteristics of the AlGaN/GaN HEMTs with $L_{\rm gd} = 5\ \mu$m before and after Si substrate removal and substrate transferring.

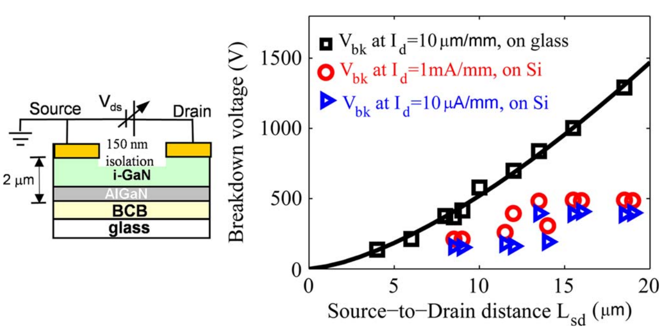


Fig. 3. Two-terminal buffer breakdown voltage as a function of $L_{\rm sd}$ of devices before and after being transferred to a glass wafer.

has also been reported in [13] and [14]. The origin of the sheet-resistance reduction is not clear at this moment. It may be due to the change of mechanical strain of the film.

The two-terminal buffer breakdown voltage ($V_{\rm bk}$) was measured on structures where source and drain contacts were isolated by 150-nm-deep $BCl_3/Cl_2$ plasma etching, as shown in Fig. 3. The breakdown voltage is defined as the voltage when the leakage current reaches 10 $\mu$A/mm. As shown in Fig. 3, the breakdown voltage of the devices on the Si substrate saturates around 500 V for source-to-drain distances ($L_{\rm sd}$) above 14 $\mu$m. However, no buffer breakdown saturation is observed after the removal of the Si substrate, which is a direct proof that the Si substrate is the limiting factor for the maximum breakdown voltage of the AlGaN/GaN-on-Si HEMTs.

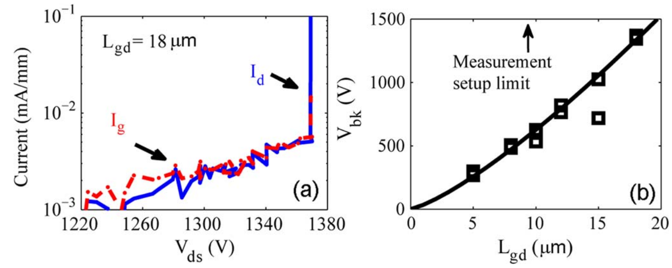


Fig. 4. (a) Three-terminal leakage current for an AlGaN/GaN HEMT on glass with $L_{\rm gd} = 18\ \mu$m at $V_{\rm gs} = -8$ V. For $V_{\rm ds} < 1220$ V, the leakage current is below the sensitivity of our measurement setup (1 $\mu$A/mm). (b) Three-terminal $V_{\rm bk}$ as a function of $L_{\rm gd}$.

By fitting the data of $V_{\rm bk}$ as a function of $L_{\rm sd}$ in the devices transferred to the glass wafer, a relation $V_{\rm bk} \sim L_{\rm sd}^{1.50}$ is extracted with the exponential coefficient in a 95% confidence bound of (1.38, 1.62). This dependence suggests the space-charge-limited (SCL) transport [15] in the leakage current. According to the SCL transport theory, the current can be expressed as $J = 9\varepsilon\mu V^2/8L^3$ ($\varepsilon$ is the dielectric constant; $\mu$ is effective carrier mobility including trapping effect; $V$ is the applied voltage, and $L$ is the distance between the two contacts). For a constant current ($I_d = 10\ \mu$A/mm for the $V_{\rm bk}$ measurement), the applied voltage between the two contacts can therefore be expressed as $V = \sqrt{8J/9\varepsilon\mu}L^{1.5}$. However, further investigation is needed to confirm the presence of the SCL transport in these devices.

The three-terminal $V_{\rm bk}$ of the AlGaN/GaN HEMTs transferred to a glass wafer was measured at $V_{\rm gs} = -8$ V. As shown in Fig. 4(a), a device with $L_{\rm gd} = 18\ \mu$m shows a $V_{\rm bk}$ of 1370 V at $I_d = 10\,\mu$A/mm. As the drain-to-source leakage is negligible, the drain-to-gate leakage limits the breakdown in these devices. $V_{\rm bk}$ as a function of $L_{\rm gd}$ is shown in Fig. 4(b). Devices with $L_{\rm gd} = 20\,\mu$m did not break down within the 1500 V measurement range of our measurement setup.

To explain the three-terminal breakdown data using the SCL transport model, the electric field at the Schottky gate contact needs to be considered. By combining (1)–(3) for the electron-conducting current

$$J = e\mu n E \tag{1}$$

$$dE/dx = -en/\varepsilon \tag{2}$$

$$V_{\rm dg} = \int_0^{L_{\rm gd}} E\, dx \tag{3}$$

where $J$ is the current density, $e$ is the electron charge, $\mu$ is the effective mobility including trapping effect, $n$ is the electron concentration, $E$ is the electric field strength, and $V_{\rm dg}$ is the drain-to-gate voltage, we get

$$V_{\rm dg} = A\left[\left(2L_{\rm gd}/A + E_{\rm in}^2\right)^{1.5} - E_{\rm in}^3\right]\Big/3 \tag{4}$$

where $A = \varepsilon\mu/J$ and $E_{\rm in}$ is the electric field at the gate.

Since the gate voltage is much smaller than the drain voltage $V_{\rm ds}$, (4) can be written as

$$V_{\rm ds} \cong V_{\rm dg} = A\left[\left(2L_{\rm gd}/A + E_{\rm in}^2\right)^{1.5} - E_{\rm in}^3\right]\Big/3. \tag{5}$$

Fitting the data of $V_{\rm bk}$ versus $L_{\rm gd}$ in Fig. 4(b), $E_{\rm in}$ is extracted to be 0.46 MV/cm in a 95% confidence bound of

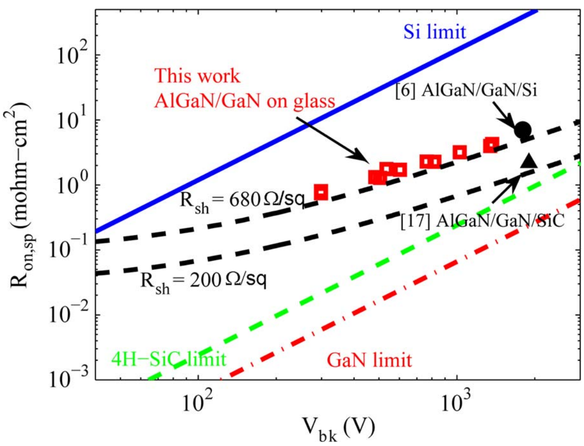


Fig. 5. $R_{\mathrm{on,sp}}$–$V_{\mathrm{bk}}$ plot of AlGaN/GaN HEMTs transferred to a glass wafer. The figure also shows the highest breakdown voltage reported for an AlGaN/GaN-on-Si HEMT (total epitaxial thickness of 6 $\mu$m) [6] and for an AlGaN/GaN-on-SiC transistor [17].

(0.35 MV/cm, 0.57 MV/cm), and $A = \varepsilon\mu/J$ is 0.0054 $\mu\mathrm{m}^3/\mathrm{V}^2$ in a 95% confidence bound of (0.0032 $\mu\mathrm{m}^3/\mathrm{V}^2$, 0.0075 $\mu\mathrm{m}^3/\mathrm{V}^2$).

From (1)–(3), the electric field at the drain contact can be calculated

$$E_{\mathrm{drain}} = \sqrt{2L_{\mathrm{gd}}/A + E_{\mathrm{in}}^2}.$$

For a device with $L_{\mathrm{gd}} = 20$ $\mu$m, at the onset of breakdown at $I_d = 10$ $\mu$A/mm, the electric field at the drain contact is between 0.81 and 1.25 MV/cm, which is smaller than the critical electric field of the GaN. This result shows that even after removing the Si substrate, the breakdown voltage of these devices is not limited by impact ionization.

The specific on resistance $(R_{\mathrm{on,sp}})$ of these devices was extracted from the $I$–$V$ characteristics (Fig. 2) and using the active area between the source and drain contacts, including a 2-$\mu$m transfer length from the contact pads. The plot of $V_{\mathrm{bk}}$ versus $R_{\mathrm{on,sp}}$ is shown in Fig. 5, where the theoretical limit lines of Si, SiC, and GaN are calculated using the equation $R_{\mathrm{on,sp}} = 4V_{\mathrm{bk}}^2/(\varepsilon\mu E_c^3)$ in [16]. The measured data of the AlGaN/GaN HEMTs on the glass substrate deviate from the GaN-limit line, particularly in the lower voltage range. A better theoretical GaN-limit line of our devices can be calculated by combining (5) with (6) and (7)

$$R_{\mathrm{on,sp}} = R_{\mathrm{sh}}L_{\mathrm{sd}}(L_{\mathrm{sd}} + L_{\mathrm{pads}}) + 2R_cW(L_{\mathrm{sd}} + L_{\mathrm{pads}}) \quad (6)$$

$$L_{\mathrm{sd}} = L_{\mathrm{gs}} + L_g + L_{\mathrm{gd}} \quad (7)$$

where $R_{\mathrm{sh}}$ is the sheet resistance $(R_{\mathrm{sh}} = 680\ \Omega/\square)$, $R_c$ is the contact resistance ($R_cW = 0.66\ \Omega \cdot \mathrm{mm}$ from the TLM measurement), and $L_{\mathrm{pads}}$ is the transfer length from source and drain contact pads (2 $\mu$m in the calculation). The calculated $R_{\mathrm{on,sp}}$–$V_{\mathrm{bk}}$ curve is plotted and shown in Fig. 5. Reducing the $R_{\mathrm{sh}}$ is very effective in reducing the $R_{\mathrm{on,sp}}$, as shown in Fig. 5, by the line for $R_{\mathrm{sh}} = 200\ \Omega/\square$. Such low sheet resistance has been demonstrated in [18].

## IV. Summary

This letter has demonstrated a new substrate-transfer technology to improve the breakdown voltage of AlGaN/GaN HEMTs grown on Si substrates. By removing the Si substrate and transferring the AlGaN/GaN HEMTs to a glass wafer, a device with $R_{\mathrm{on}} = 20.6\ \Omega \cdot \mathrm{mm}$ and $L_{\mathrm{sd}} = 23.5$ $\mu$m showed a more than 1500-V breakdown voltage and $R_{\mathrm{on,sp}}$ of 5.3 $\mathrm{m}\Omega \cdot \mathrm{cm}^2$ for only 2-$\mu$m total epilayer thickness. The performance of the devices can be improved even further by bonding the GaN epilayer to a carrier wafer with higher thermal conductivity, such as the polycrystalline AlN wafers.

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